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**METHOD AND SYSTEM FOR MONITORING TIRE PRESSURE IN VEHICLES  
EQUIPPED WITH ANTI-LOCK BRAKING SYSTEMS**

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# METHOD AND SYSTEM FOR MONITORING TIRE PRESSURE IN VEHICLES EQUIPPED WITH ANTI-LOCK BRAKING SYSTEMS

## BACKGROUND OF THE INVENTION

The present invention is directed to a method and system for monitoring tire pressure in a vehicle equipped with an anti-lock braking system (ABS) based on the deviation of tire pressure of at least one tire from a reference value.

Safety and reliability are central aspects of automotive engineering. Tire pressure is an important aspect in this regard. Loss of tire pressure has been recognized to be a significant factor in road traffic accidents. 85% of tire failures are a consequence of a creeping pressure loss. Incidentally, correctly adjusted tire pressure ensures optimal driving comfort at all times in terms of rolling noise, vertical bumpiness and sensitivity to transverse expansion joints.

It is known that tire pressure can be monitored directly by means of pressure sensors on two-axle or three-axle vehicles (see ATZ Automobiltechnische Zeitschrift 102 (2000) 11, pp. 950 ff.). The pressure sensors are mounted on the tire and rotate with the wheel. The pressure sensors are equipped with a high-frequency transmitter (HF transmitter) which transmits the measured pressure values to a receiver disposed in the motor vehicle and signals pressure losses to the driver. This functions both during travel and when the vehicle is stationary. Since this approach is based purely on measurement, the costs are relatively high, especially if all wheels are being monitored.

It is also known that tire pressure can be monitored indirectly by means of ABS wheel sensors (see ATZ Automobiltechnische Zeitschrift 94 (1992) 6, pp. 336-340; EP 0 489 562 B1; EP 0 489 563 B1 and EP 0 607 690 B1). Tire pressure also affects the rolling circumference of the tires. The speed of rotation of the wheels determined by means of the

wheel sensors of the ABS depends on the rolling circumference of the wheels. If, during travel in a straight line without braking, the speed of rotation of a wheel changes relative to the reference speed of the other wheels or of one other wheel, this represents an indicator of a change in rolling circumference of the wheel in question as a result of pressure loss from the tire or of separation of pieces of tire at the tire circumference or of a variation in loading. Any change of rolling circumference is interpreted as a pressure change.

The known methods of monitoring tire pressure are imprecise and are capable of detecting only large and suddenly occurring pressure changes.

Accordingly, it is desired to provide a method and system for monitoring tire pressure that permit detection of small and creeping tire pressure losses.

### **SUMMARY OF THE INVENTION**

Generally speaking, in accordance with the present invention, a method and system for monitoring vehicle tire pressure are provided which overcome disadvantages associated with prior art methods and systems.

The tire pressure monitoring system and method according to the present invention are provided for vehicles equipped with anti-lock braking systems, especially vehicles having more than two axles. ABS wheel sensors on the wheels of at least one axle sense variables which depend on wheel rotation such as the travel distances covered by the wheels or the speeds of rotation of the wheels. An ABS control unit adds the variables of the individual wheels on the respective diagonals relative to the wheel arrangement of the vehicle. Recognition of an undesired (insufficient) tire pressure condition takes place when the diagonal sums differ from one another by more than a preselected limit value. Furthermore, monitoring of the variables takes place in a plurality of monitoring cycles, recognition of an undesired tire pressure

condition taking place when the deviations of the diagonal sums exceed a summation limit value defined for all monitoring cycles. Thus, it is possible to achieve improved accuracy and sensitivity in the recognition of undesired tire pressure conditions.

An embodiment of the present invention utilizes a combination of direct tire pressure measurement by means of pressure sensors of a tire pressure measuring system and indirect tire pressure determination using the wheel sensors. It is therefore possible to substitute pressure sensors of the tire pressure measuring system by ABS wheel sensors and/or to use the ABS control device for evaluation of the measured signals of the tire pressure measuring system as well, whereby components and costs can be saved without impairing the reliability and safety of tire pressure monitoring. The actual tire pressures determined by means of pressure sensors support the values determined indirectly by means of the ABS.

Accordingly, it is an object of the present invention to provide a method and system for monitoring tire pressure in vehicles, including vehicles equipped with ABS.

It is also an object of the present invention to provide a method and system for tire pressure monitoring that are cost-effective and that react more sensitively to small and creeping pressure losses.

It is another object of the present invention to provide a method and system for tire pressure monitoring which provide for both direct and indirect pressure determination.

Still other objects and advantages of the present invention will in part be obvious and will in part be apparent from the specification.

The present invention accordingly comprises the several steps and the relation of one or more of such steps with respect to each of the others, and embodies features of construction, combination of elements, and arrangement of parts which are adapted to effect such

steps, all as exemplified in the detailed disclosure hereinafter set forth, and the scope of the invention will be indicated in the claims.

### **BRIEF DESCRIPTION OF THE DRAWINGS**

For a fuller understanding of the invention, reference is had to the following description taken in connection with the accompanying drawings in which:

Figs. 1-9 are schematics depicting various embodiments of the tire pressure monitoring system according to the present invention applied to three-axle vehicles;

Fig. 10 is a block diagram of an ABS control device with integrated control unit of a tire pressure measuring system employed in the tire pressure monitoring system according to the present invention;

Fig. 11 is a block diagram of a device for determining travel distance according to the tire pressure monitoring system of the present invention; and

Fig. 12 is a graph showing the number of periods counted by a count register of the device shown in Fig. 11 plotted against travel distance, according to the present invention.

### **DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS**

Referring to the drawing figures where like reference numerals are used for corresponding elements, Figs. 1 to 9 schematically show three-axle vehicles 4 equipped with anti-lock braking systems (ABS) 2 and tire pressure measuring systems 12. The ABS and tire pressure measuring systems are combined to yield a tire pressure monitoring system. Although the following detailed description refers to three-axle vehicles, it should be understood that the present invention also has application for vehicles with  $(2 + n)$  axles, where  $n \geq 0$ , or, in other words, vehicles with two or more axles.

Three-axle vehicles 4 are each provided with a front axle A1, which is provided with a right front wheel A1r and a left front wheel A1l, a driving axle A2, which is provided with right dual wheels A2r and left dual wheels A2l, and a third axle A3, which is provided with right dual wheels A3r and left dual wheels A3l. It should be appreciated that single tires can also be used instead of dual tires.

ABS 2 preferably comprises an ABS control unit 6 and a Controller Area Network (CAN) interface 8. Wheel sensors and brake pressure modulators (shown in the drawings as blocks 25, 26, 27, 28, 29, 30) are allocated to the wheels of at least one of the three axles A1, A2, A3. ABS control unit 6 determines the speed of rotation of the wheels or the travel distance covered from the signals of the wheel sensors. A change in rolling radius due to tire pressure loss is recognized by increasing speed of rotation of the wheel or decreasing travel distance and is desirably indicated to the driver on a display 10. Influences on the rolling radius and thus on the speed of rotation of the wheels or on the travel distance covered due to special situations such as cornering, acceleration, deceleration, high speed, wheel load (loading) and abrasion can be compensated for by suitable comparisons of the speeds of rotation of the wheels or travel distances per axle, per side and/or per diagonal and/or by comparisons with threshold values.

For each wheel of at least one of the three axles, tire pressure measuring system 12 is provided with a wheel electronics package 31, 32, 33, 34, 35, 36, 37, 38, 39, 40 which is desirably disposed in or on the tire and comprises a sensor, a signal-processing stage, an HF transmitter stage and a battery as the power source. It should be understood that a power source other than a battery may be used such as, for example, an external power supply by means of transponder technology.

Each wheel electronics package forms with its respective tire inflation valve a unit that is desirably mounted on the rim of the wheel. The sensor is provided with a pressure sensor which measures the pressure in the tire and a device for measured-value acquisition and signal conditioning. The sensor controls a digital module in which there is integrated the HF transmitter stage that transmits the measured data to a receiver/evaluation unit 42, desirably with CAN interface 44, in the 433 MHz range, for example. Each wheel electronics package preferably has its own identifier, which is also transmitted.

The respective adjusted tire pressure is initialized by the driver, or the system refers back to setpoint pressures input for the vehicle types in question, in which case the system checks the adjusted pressures for plausibility. A wheel change or replacement is recognized by the system in terms of position on the vehicle. Any decrease in tire pressure – both while the vehicle is stationary or in motion – is desirably displayed to the driver on display 10 by receiver/evaluation unit 42.

Fig. 1 shows an embodiment of a tire pressure monitoring system according to the present invention that uses a 6-channel ABS 2, which is provided with wheel sensors and brake pressure modulators 25, 26, 27, 28, 29, 30 on all three axles, and a tire pressure measuring system 12 with ten wheel electronics packages 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, each wheel of each axle being provided with a wheel electronics package. The ABS for indirect determination of the tire pressures and the tire pressure measuring system can operate in parallel and independently.

Fig. 2 shows an embodiment of a tire pressure monitoring system according to the present invention that uses a 4-channel ABS. The system shown in Fig. 2 differs from the system shown in Fig. 1 in that only four sensors and four brake pressure modulators 25, 26, 27,

28 are provided for the first and second axles A1 and A2 and the third axle is not monitored for ABS control but is indirectly regulated. Direct pressure measurement by tire pressure measuring system 12 takes place as in the system shown in Fig. 1 on all wheels of all axles. In the embodiment shown in Fig. 2, two ABS wheel sensors and two ABS pole wheels are saved.

Fig. 3 shows an embodiment of a tire pressure monitoring system according to the present invention in which the ABS used for tire pressure monitoring is provided, as in Fig. 2, with four sensors and four brake pressure modulators 25, 26, 27, 28, specifically on the first and second axles A1 and A2. However, in contrast to the embodiments shown in Figs. 1 and 2, wheel electronics packages 33, 34, 35, 36, 37, 38, 39, 40 of tire pressure measuring system 12 are provided for only the dual wheels of second and third axles A2 and A3. No wheel electronics packages are provided on the wheels of front axle A1. Furthermore, in contrast to the embodiments depicted in Figs. 1 and 2, receiver/evaluation unit 42 of tire pressure measuring system 12 is integrated in the housing of the ABS control unit, the ABS computer also performing the evaluation of the measured signals of the wheel electronics packages. In this way, savings are achieved as regards wheel sensors and toothed-pole wheels on the third axle and wheel electronics packages on the first axle and also as regards the separate evaluation device and CAN interface as well as the separate housing of the tire pressure measuring system in the embodiments shown in Figs. 1 and 2.

In the embodiment depicted in Fig. 3, a diagonal comparison is made of the sum of the speeds of rotation of the wheels or travel distances of right front wheel A1r and of the left wheel of second axle A2l with the sum of the speeds of rotation of the wheels or travel distances of left front wheel A1l and of the right wheel of second axle A2r. In the event of a decrease in tire pressure, the speed of the wheel in question will be increased compared with that of the other



wheels, or the travel distance covered will be correspondingly shorter. In the case of speed comparison, for example, positive values signify reduced pressure in right front wheel A1r or in left wheel A2l of the second axle; negative values signify reduced pressure in left front wheel A1l or in right wheel A2r of the second axle. The diagonal comparison via speed of rotation of the wheels or travel distance of the wheels of the first and second axles replaces the pressure sensors on the first axle.

Because of the diagonal comparison, cornering influences are well compensated for. The absolute tire pressures determined via the tire pressure sensors support the results from the diagonal comparison.

Fig. 4 shows an embodiment of the tire pressure monitoring system according to the present invention which differs from the system shown in Fig. 3 in that wheel electronics packages 31, 32 are provided on wheels A1r and A1l of the first axle instead of on the wheels of second axle A2. The advantage compared with the embodiment according to Fig. 3 resides in the fact that the loaded/empty ratio on the first axle, which is the front axle, is smaller than that on the second axle, and so changes in rolling radius due to loading changes are not as perceptible on the first axle as they are on the second axle or even on the third axle.

Fig. 5 shows an embodiment of the present invention which differs from the embodiments shown in Figs. 3 and 4 in that the direct pressure measurement is now performed on only the dual tires of third axle A3. Support for the indirect pressure determination via the diagonal comparison of the wheels of the first and second axles by the direct pressure measurement on the third axle can be achieved by virtue of the proximity of the second and third axles to one another. Because of this proximity, it can be assumed in the error-free case that the rates of rotation of the wheels or the speeds of rotation of the wheels on the second and third

axles are substantially identical and thus the speed values of the second axle can be transposed to the third axle.

Fig. 6 shows an embodiment of the tire pressure monitoring system according to the present invention in which wheel sensors 25, 26, 27, 28, 29, 30 of ABS 2 are provided on the wheels of all three axles A1, A2, A3. To save costs, direct measurement of tire pressures via wheel electronics packages 31, 32 is provided on only first axle A1, which is the front axle or steering axle. In contrast to the embodiments of the invention depicted in Figs. 1 and 2, it is not individual wheels but diagonal sums of the wheel speed signals or travel distances of all sensed axles that are compared with one another. Thus, cornering influences are well compensated for.

The following diagonal differences are formed in the speed comparison, where  $v$  denotes speed:

$$\text{Diagonal difference 1: } (v_{A1r} + v_{A2l}) - (v_{A1l} + v_{A2r})$$

$$\text{Diagonal difference 2: } (v_{A2r} + v_{A3l}) - (v_{A2l} + v_{A3r})$$

$$\text{Diagonal difference 3: } (v_{A1r} + v_{A3l}) - (v_{A1l} + v_{A3r})$$

Evaluation of the formation of diagonal differences yields the following results:

Diagonal difference 1	Diagonal difference 2	Diagonal difference 3	Reduced pressure
positive	0	positive	A1r
negative	0	negative	A1l
negative	positive	0	A2r
positive	negative	0	A2l
0	negative	negative	A3r
0	positive	positive	A3l

These comparisons of diagonal sums therefore create the capability of achieving reduced pressure indications specific to each wheel.

As an example, the aforesaid formation of diagonal differences is also presented below for a four-axle vehicle, in a configuration in which only three diagonal differences are formed:

Diagonal difference 1:  $(v_{A1r} + v_{A2l}) - (v_{A1l} + v_{A2r})$

Diagonal difference 2:  $(v_{A3r} + v_{A4l}) - (v_{A3l} + v_{A4r})$

Diagonal difference 3:  $(v_{A1r} + v_{A4l}) - (v_{A1l} + v_{A4r})$

Diagonal difference 1	Diagonal difference 2	Diagonal difference 3	Reduced pressure
positive	0	positive	A1r
negative	0	negative	A1l
negative	0	0	A2r
positive	0	0	A2l
0	negative	0	A3r
0	positive	0	A3l
0	negative	negative	A4r
0	positive	positive	A4l

In principle, each formation of differences in which at least one axle of one diagonal difference is also included in the calculation of another diagonal difference leads to an unequivocal correlation with a specific wheel. For a vehicle with five or more axles, therefore, a fourth diagonal difference is required.

The absolute tire pressures measured by means of wheel electronics packages 31, 32 on the first axle support the comparison of diagonal sums.

The embodiment of the present invention depicted in Fig. 6 has special advantages for the use of external tire pressure sensors that can be left on the vehicle in the event of replacement of complete wheels. This obviates the need to input the wheel identifier of the pressure sensor into the electronics via a suitable diagnostic instrument whenever a wheel is replaced. Moreover, the use of wheel electronics packages for measurement of absolute tire pressures on only the first axle (front axle or steering axle) has the advantage that there is no longer a need for costly tire pressure sensors on the second and third axles. Otherwise, double tire pressure sensors would have to be mounted on the dual wheels or two tire inflation connections would have to be connected to one another in a complex arrangement of hoses, screw couplings and tee pieces.

Because of the absolute pressure measurement on the wheels of the first axle, the two other axles can be compared with one another with greater certainty. For the comparisons of diagonal sums, the pressure measurement on the first axle permits the assumption that at least two values are determined relative to the absolute pressure level, which would not be the case if only ABS wheel sensors were being used. Thus, cost-effective, reliable and accurate tire pressure monitoring is possible.

Figs. 7 and 8 show embodiments of the present invention that differ from the embodiment depicted in Fig. 6 in that the absolute tire pressure is measured on two axles, specifically on the wheels of first axle A1 and on the wheels of second axle A2 (Fig. 7) as well as on the wheels of first axle A1 and on the wheels of third axle A3 (Fig. 8). While this

arrangement may be more complex compared with the embodiment depicted in Fig. 6, greater support for the results from the diagonal comparisons is achieved.

Fig. 9 shows an embodiment of the present invention that corresponds to the embodiment depicted in Fig. 1, with the exception that a comparison of diagonal sums is performed as in the embodiments shown in Figs. 6, 7 and 8.

Fig. 10 shows the integration of receiver/evaluation device 42 of tire pressure measuring system 12 into ABS control unit 6 of ABS 2. ABS control unit 6, HF receiver 42 of tire pressure measuring system 12, a standby microcontroller 50 as well as a CAN interface 8 (such as, for example, SAE J1939) used jointly for both systems are disposed in a common housing. The standby microcontroller is constantly ready to receive the signals of the wheel electronics packages, even when the vehicle is parked, since the wheel electronics packages constantly transmit measured pressure values. This feature is provided in the embodiments of the inventive tire pressure monitoring device according to Figs. 3 to 8. Reference symbols 25, 25' and 10 as well as 31 to 40 respectively denote an ABS wheel sensor, an ABS control valve, a display and wheel electronics packages of the tire pressure measuring system.

A device for determination of travel distance will be explained in more detail with reference to Figs. 11 and 12. Voltages transmitted by wheel sensors 25, 26, 27, 28 are filtered by input circuits 60 and converted to square-wave signals, whose half-period or whole-period durations are evaluated by at least one microcontroller 62. While only one microcontroller is shown in the drawings, it should be understood that a plurality of microcontrollers can be used. The functions for the anti-lock braking system/acceleration-slip regulation (ABS/ASR) are labeled as "period-duration measurement" and "speed computation."

The present invention preferably provides a parallel-configured travel distance determination unit, which represents a count register whose value is incremented each time the sensor voltage passes through zero. Thus, the travel distance can be determined simply by counting the periods of the sensor signals.

If microcontroller 62 evaluates only whole periods or multiples thereof, the travel distance counter (count register) is incremented only upon each corresponding passage through zero. If the microcontroller is to choose between these possibilities as a function of speed, it is desirable to choose incrementation which corresponds to the multiple of one half period. The number of passages through zero depends on the tire rolling circumference and on the number of teeth of the pole wheel. The count values are assessed constantly by a comparator 64 or only upon overflow of the count register with the highest achieved count number.

For example, for a rolling circumference of 3,425 mm and a pole wheel with 100 teeth, each passage through zero represents a travel distance of 17.125 mm. After a target travel distance of, for example, 1 km, the count values reached are compared with one another. As a digital measure, assessment of the achieved count values can be initiated when the count value leads to overflow of the count register. For 16-bit count registers, overflow takes place when the count value has been incremented to  $65,535$  ( $2^{16} - 1$ ).  $65,535 + 1$  is equal to zero, since the 17<sup>th</sup> place of the binary number is not available (see Fig. 12). The count value of  $2^{16} = 65,536$  corresponds to 1.122 km. This in turn corresponds to a resolution of  $1/65536$  or 0.0015%.

Wheel speed has been found to increase by about 0.5% per bar of pressure loss. This means that the period duration and thus the travel distance of a tooth decreases by about 0.5% per bar. Since 100 teeth represent the rolling circumference of the tire, this is also reduced by the cited percentage. The favorable resolution (measurement accuracy) indicated hereinabove

in the present example is greater by a factor of 328 than the influence of pressure loss (per bar) that is measured.

The count results obtained are preferably weighted. As with computation of when the ASR threshold is exceeded, the difference between wheels on the same side is desirably given greater weight than that between wheels disposed on the same axle or on the same diagonal.

It should be appreciated that, by virtue of the counting of the respective travel distances covered using the ABS wheel sensors, only a few conversion steps are necessary - fewer than in prior art methods - and, as a result, greater computing accuracy can be achieved, especially through the use of computers. A smaller number of conversion steps has the advantage that rounding is applied less frequently and values to the right of the decimal point are disregarded less frequently in the computation.

The determination of travel distance can be paused or stopped and restarted, for example when a nonsteady driving situation is recognized, such as anti-lock braking, acceleration slip regulation, cornering or even driving at low speed.

The inventive device for determination of travel distance functions independently of speed. No further expense is necessary either to improve the speed computation or to filter the result drastically in order to eliminate transient fluctuations. There is no need to allow for measurement uncertainties, such as rounding errors in the speed computation. The travel distance covered by the wheel is determined directly, without the need for another computational variable. The determined travel distance forms an integral, and so fluctuations of individual period durations caused by roadway asperities, for example, have no influence.

It will thus be seen that the objects set forth above, among those made apparent from the preceding description, are efficiently attained and, since certain changes may be made in carrying out the above method and in the constructions set forth without departing from the spirit and scope of the invention, it is intended that all matter contained in the above description and shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

It is also to be understood that the following claims are intended to cover all of the generic and specific features of the invention herein described and all statements of the scope of the invention which, as a matter of language, might be said to fall therebetween.